Spatial Variation of Wind Stress and Wave Field In the Shoaling Zone

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Document #N00014-97-F-0123

LONG-TERM GOALS

Existing atmospheric models for predicting surface stress and turbulent structure in the shoaling zone fail because of their inability to properly account for wave age, shoaling and internal boundary layer development. Accurate model simulation of the surface stress and turbulence above the air-sea interface is important for a number of applications including understanding wave growth and decay. Under this ONR Advanced Research Initiative our goals are:

1. to measure the spatial variation of the wind, surface stress and ocean wave fields in the shoaling zone and to provide quality-controlled data to the shoaling community; and

2. to study the relationship between the spatial varying mean wind, stress, turbulence structures, and surface wave fields in order to model effects of wave age, shoaling, and internal boundary layer development on the drag coefficient and momentum transfer.

OBJECTIVES

The key to achieving our goals is the development of a data archive containing simultaneous observations of the spatially varying wave, wind and stress fields in the shoaling zone. Currently instrument systems for making such observations do not exist. Therefore, our first objective is development and test of an efficient measurement system. This report focuses on the instrument system developed and its application in a pilot study.

APPROACH

NOAA's LongEZ research aircraft (www.arl.noaa.gov/frd/LongEZ) is well known for its high fidelity observations of mean meteorological parameters and mass, momentum and energy flux in marine boundary layers. A needed component was the ability to measure wave height, phase speed and directional spectra. To add wave measurements we proposed the addition of a pod containing a Ka-band radar and laser array to the LongEZ's instrument system. With such a novel airborne system we could, for the first time, freely explore the spatially developing wind, surface stress and wave field within the shoaling wave zone.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Spatial Variation of Wind Stress and Wave Field in the Shoaling Zone**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NOAA/Field Research Division,1750 Foote Drive,Idaho Falls,ID,83402**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

During the first year of funding, we designed, installed and tested the Ka-band radar and laser-array. The radar, designed by Doug Vandemark (http://rows.wff.nasa.gov/dls.html) observes mean surface slope over wave scales from 1m down to 1 cm. Observation of small (capillary) waves is important since short-scale waves strongly influence aerodynamic roughness and therefore shear stress. The laser array consists of three "down-looking" lasers mounted in a triangular arrangement with 1 m separation distances. The lasers measure distance to ±2 mm at 50 Hz (i.e., at nominal ground speeds of 50 m/s with 1 m spatial resolution) and work similar to a wave-wire system. However, additional complexity is imposed as aircraft translation and rotational motions must be removed during data reduction. This year's effort focused on the test of this instrument system during our pilot experiment, development of data reduction procedures and reduction and archive of the pilot study data. The performance of the new lasers and radar instrument systems exceeded our expectations.

During the November 1977 pilot experiment the new instruments were tested in a pilot experiment of 50 flight hours. We flew several flight patterns off the Field Research Facility (FRF) pier at Duck NC. Drs Jielun Sun and Larry Mahrt are focusing on the analysis of these data. Since our primary task is instrument development, pilot study completion and data archive, our analysis is more limited in scope. Details on the experiment, data and its analysis are at http://mist.oce.orst.edu/shoaling/shoaling.html.

A primary focus of the pilot experiment was to assess the spatial and temporal variations in winds, surface fluxes of mass momentum and energy, and to characterize the underlying wave field in various regions of the shoaling zone. Thus analyses initially focused on two main areas: reduction of the high frequency wind measurements to determine surface stress magnitudes, and development of data reduction software for the laser array data to determine sea surface heights (SSH) and subsequently wave structure.

RESULTS

1. Atmospheric stress measurements

To compute momentum fluxes a 3 km (60 sec) symmetrical running mean was used to determine the wind fluctuations. The choice of a 3 km mean was validated with cospectral analysis of horizontal and vertical wind signals from 16 km transect. No significant energy was contributed to the momentum flux at frequencies lower than those corresponding to 3 km. Also, mean removal was accomplished using spatial averaging as opposed to a time mean in order to eliminate potential measurement bias caused by aircraft speed variations.

In order to assess changes in atmospheric turbulence as one moves through a shoaling region, repeated transects were flown perpendicular to the shoreline from a point approximately 10 km WSW of the Duck Pier over Currituck Sound to a point approximately 90 km offshore. Nominal altitudes of these measurements were 20 m. A 1000 m flux averaging scale was chosen to characterize the stress variations along this transect. Recall that this averaging scale is not the same as the mean removal averaging scale. In theory one could chose any flux averaging distance although the smaller the scale the more noisy the measurements. It is the mean removal scale which is the critical choice. If too small it will reject some eddies that contribute to the flux. If too large it may smooth mesoscale changes in the mean state.

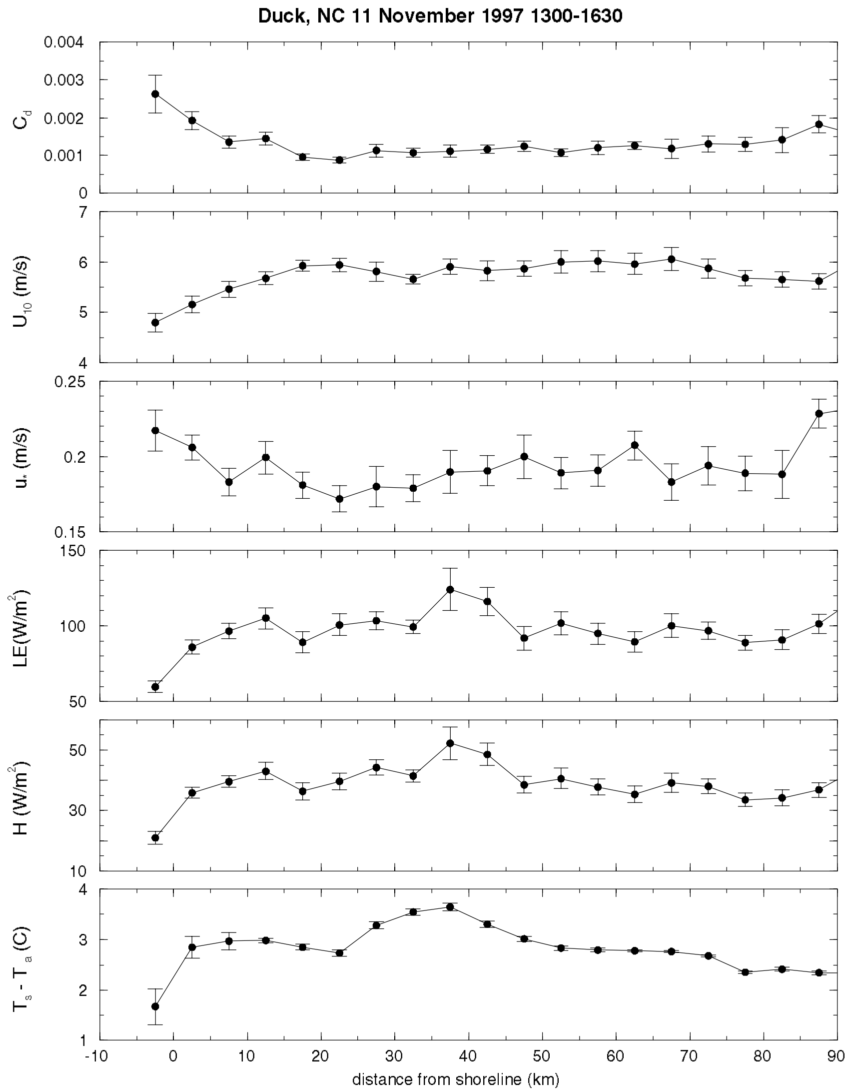

Figure 1: Variation of the atmospheric drag coefficient C_d, the 10 meter wind speed U_{10}, the friction velocity u_*, the latent heat flux LE, the sensible heat flux H_s, and the air-sea temperature difference T_s - T_a as a function of distance from shore. Note the failure of the traditional near linear parameterization of the drag coefficient with the 10 m wind speed as the distance from shore becomes less than 20 km.

Figure 2 shows an analysis of a number of variables on 11 November 1997 for repeated passes along the track mentioned above. The zero point in the abscissa represents the eastern shoreline adjacent to the FRF Pier while negative values represent measurements extending in the southwest direction. The width of the land area west of the pier is approximately 1 km. Error bars represent standard errors where the number of points in each bin of the data ranged from 17 to 37.

Offshore sensible heat fluxes are generally small, near 40 W/m^2, while latent heat fluxes appear greater by a factor of three. Wind speeds extrapolated to 10 m heights are near 6 m/s and are essentially from the north ranging from 350 to 10 degrees. The low virtual heat fluxes indicate a near-neutral stability regime. Note the good agreement between the sea-surface ambient air temperature difference and the sensible heat flux.

The upper three traces demonstrate a key hypothesis of this study, namely, that the drag laws used for the open sea begin to break down within a shoaling region. Open-sea drag laws generally parameterize drag coefficients with the 10 meter wind speed where there is an approximately linear increase in the drag coefficient with wind speed. Applying this relationship with suggested constants and the winds shown would produce drag coefficients near 1.1×10^{-3}, in good agreement with the data observed a few tens of kilometers or greater offshore. However, as the shoreline is approached near 20 km, an inverse relationship with between the drag coefficient and the wind speed becomes apparent. This demonstrates the need for additional parameterization of the drag coefficient to include wave influences.

2. Surface wave characteristic measurements

To measure wave characteristics, the laser measurements must be rotated from aircraft to earth coordinates. Mathematically, this was accomplished by defining a laser displacement matrix and a laser measurement matrix. These matrices were then rotated with aircraft roll, pitch and heading angles. On the LongEZ, these angles are also measured to ±0.05 degrees at 50Hz. Once the coordinate transformation was applied the wave heights were resolved by operating on the vertical components. This required removing the aircraft altitudes and removing the mean apparent sea level height.

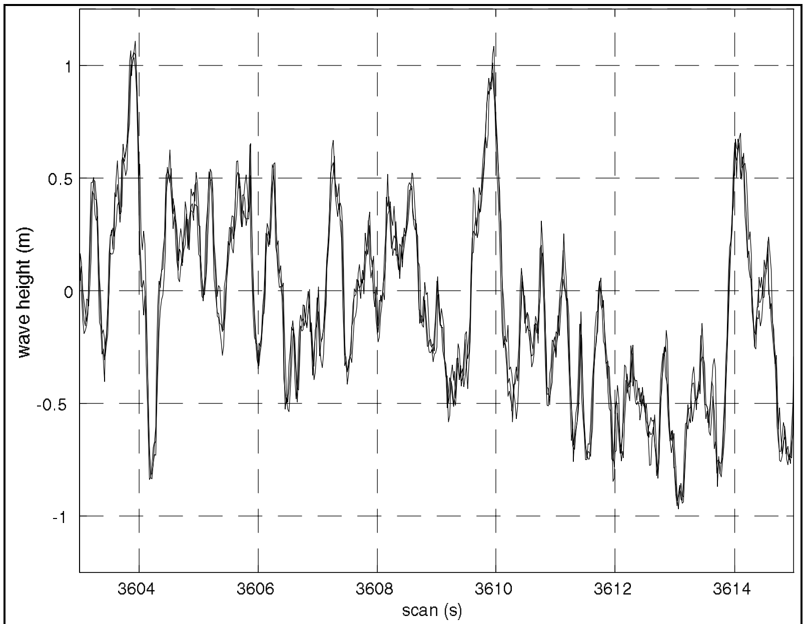

Figure 2: Sample wave heights derived from the downward-looking three laser array mounted on the Long-EZ aircraft. The aircraft was moving at approximately 45 m/s directly into the wind at a height of 18 m above sea level approximately 50 km offshore.

Figure 3 shows sample wave heights derived from the three laser signals for a discrete transect flown approximately 50 km offshore. The flight heading was 35 degrees, almost directly into the mean wind, while the mean ground speed and measurement height was 45.0 m/s and 18.4 m respectively. Wave structure can clearly be identified in the figure with maximum amplitudes near 1 m. For this particular data set, changes in the apparent mean sea level height of less than 20 cm fall within the error limits of the measurement system's ability to resolve absolute heights. The resolution of the GPS system's determination of absolute height is not less than 20 cm. In determining the aircraft heights, accelerometers mounted near the lasers are integrated and blended with GPS-derived velocities by combining high frequency contributions of the former with low frequency signal portions of the latter. These velocities are then integrated and combined with the GPS heights to determine more accurately the aircraft altitudes. Nevertheless we operate near the limit of detection on the larger scales, The decrease of the average sea level height of approximately 0.5 m over a 180 m distance (4 s × 45 m/s = 180 m) between scans 3610 and 3614 in Figure 2 is not clearly real. We expect to improve altitude accuracy to around 5 cm by our next study.

Wave heights spectra help identify the dominant scales. Figure 4 shows a spectrum from Laser 1, mounted in the port strake of the aircraft. The peak normalized frequency is 0.362 which, given the mean aircraft height and ground speed, corresponds to a horizontal scale of 50.8 m. A number of spectra have been generated for a "box" pattern flown offshore to analyze the consistency of the wave data. Current efforts focus on determining wave phase speeds in order to determine wave ages, which are expected to influence drag coefficients. Once these analyses are completed they will then be related to the changes in the drag coefficients observed.

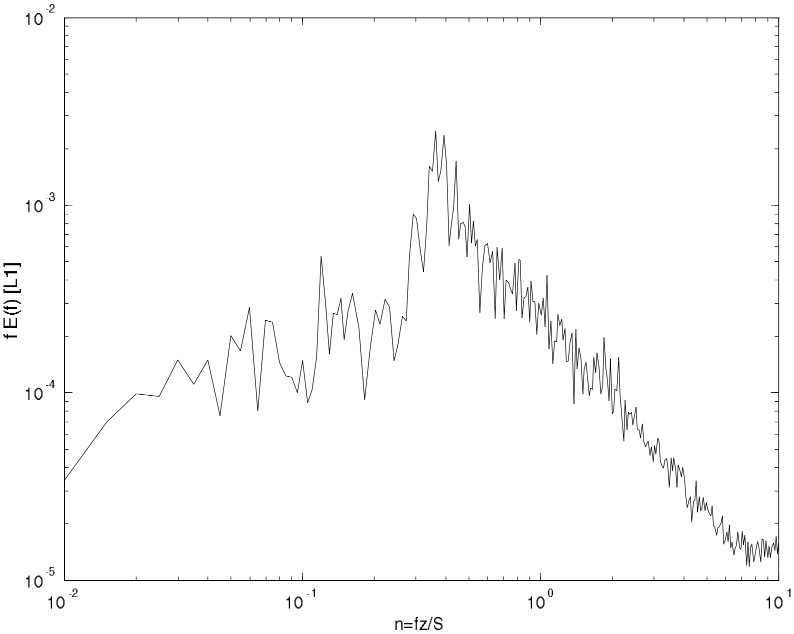

Figure 3: Energy spectrum of wave height measurements from Laser 1 over a 16 km transect for the same data run shown in Figure 2. The peak normalized frequency near 0.36 indicates a dominant scale of 50.8 m.

IMPACT/APPLICATIONS

Our laser array approach has proved very successful and is now being adapted by others. NASA, recognizing the power of airborne laser wave measurements, has funded a study to reduce the uncertainty in the electromagnetic (EM) range bias that corrupts satellite sea surface topography measurements. LongEZ based laser measurements will be used in the study to refine EM bias models for large-scale tilt, short-scale diffraction, and hydrodynamic effects.

TRANSITIONS

We have been advising Dr. Mark Donelan on the development of this system on his research ship. The pilot study data archive is being analyzed in detail by Drs Jielun Sun and Larry Mahrt.

RELATED PROJECTS

Although funded separately, this project is a highly cooperative effort with Doug Vandemark (N0001497F0179 -- Ka band radar development and analysis, NASA), Jielun Sun (N00014-0-98-1-0245 -- data interpretation, NCAR) and Larry Mahrt (N00014-0-98-1-0282 -- data interpretation, OSU).

PUBLICATIONS

Dobosy, R. J., T. L. Crawford, D. Vandemark, C. A. Vogel, 1999: Measurement of Ocean Surface in Shoaling Zones by Laser Array. *Fourth International Airborne Remote Sensing Conference and Exhibition*, ERIM International, 21-24 Jun., Ottawa, Ontario, Canada

Sun, J., L. Mahrt, D. Vickers, J. Wong, T. Crawford, C. Vogel, E. Dumas, P. Mourad, D. Vandemark, 1999: Air-Sea Interaction in the Coastal Shoaling Zone. *13th Symposium on Boundary Layers and Turbulence*, American Meteorological Society, 10-15 Jan., Dallas, TX.

Vogel, C. A., T. L. Crawford, J. Sun, L. Mahrt, 1999: Spatial Variation of the Atmospheric Surface Drag Coefficient Within a Coastal Shoaling Zone. *13th Symposium on Boundary Layers and Turbulence*, American Meteorological Society, 10-15 Jan., Dallas, TX.

IN-HOUSE/OUT-OF-HOUSE RATIOS

Within NOAA, this effort is a cooperative one with half the work carried out by Oak Ridge Associated Universities staff on assignment to NOAA. Also, research scientist and students at NCAR and OSU are working on this project.